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Summer Frost in Young Forest Plantations

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Summer Frost in Young Forest Plantations

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1 INTRODUCTION

Frost during the active growing season has been observed to be a major cause of conifer seedling mortality and reduced plantation performance in research trials (Black *et al.* 1987, 1988; Coates 1988; Vyse 1988; Sutherland[1]) and operational plantings (O. Steen and A. Vyse, pers. comm.) throughout the southern and central interior of British Columbia. Although the extent of land subject to summer frost is still unknown, preliminary evidence suggests that the problem is serious and significantly limits successful Engelmann spruce and Douglas-fir regeneration in all of the interior biogeoclimatic zones (IDF, SBS, SBPS, MS, ICH, and ESSF). Seedling-height air temperature measurements from a number of research sites throughout the Interior (Figure 1) suggest that potentially damaging frosts can occur at any time during the summer on a wide range of site types.

The objectives of this report are to describe the physical principles governing the causes and occurrence of frost and the effects of frost on conifer seedlings; to identify frost-prone sites; and to present techniques for avoiding or preventing frost problems in young plantations.

An understanding of the physical principles should help foresters to identify high risk summer frost sites and to prescribe appropriate harvesting methods, vegetation management treatments, site preparation treatments, and species for these sites.

2 CAUSES AND OCCURRENCE OF SUMMER FROST

2.1 Radiation and Advection Frost

Frost is defined as the condition that exists when the temperature falls below 0°C, the freezing point of pure water. A hoarfrost, or white frost, occurs when water vapour in the air condenses onto a frozen surface and forms ice crystals. A black frost occurs when the surface freezes, but the air is too dry for condensation to occur.

There are two different processes that cause frost and affect its occurrence throughout the landscape. A radiation frost occurs on calm, clear nights when the ground surface cools by radiating heat toward the atmosphere. Under these conditions, frost occurs at the ground surface even though the air temperature above the ground is well above the freezing point, as shown in Figure 2. An advection frost occurs when air that has radiatively cooled below the freezing point at another location, flows or is blown (is advected) onto a site. Advection frosts occur on a wide range of areal scales, from large scale frontal activity (such as a cold arctic air mass), to local scale downslope flow of dense cold air, to small scale cold air ponding in gently rolling terrain. The actual distinction between a radiation frost and an advection frost is somewhat arbitrary since both processes usually occur simultaneously.

To predict where frost is most likely to occur, it is important to understand the conditions that cause radiative cooling at the ground surface and to know what happens to air as it cools. The movement of cold air significantly affects the frequency and severity of frosts. It also affects the locations on the landscape where frost most commonly occurs.

Nocturnal surface cooling depends on a complex interaction of atmospheric conditions and site characteristics. A summary of the major factors affecting frost occurrence is outlined in Table 1. The role of the many factors that affect nocturnal cooling is discussed in more detail below.

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[1] Sutherland, C. 1989. Improving plantation performance of Douglas-fir and lodgepole pine with mechanical site preparation and fencing in IDFb and SBSk subzones. Unpubl. First Year Interim Report. B.C. Min. For., Cariboo Forest Region.

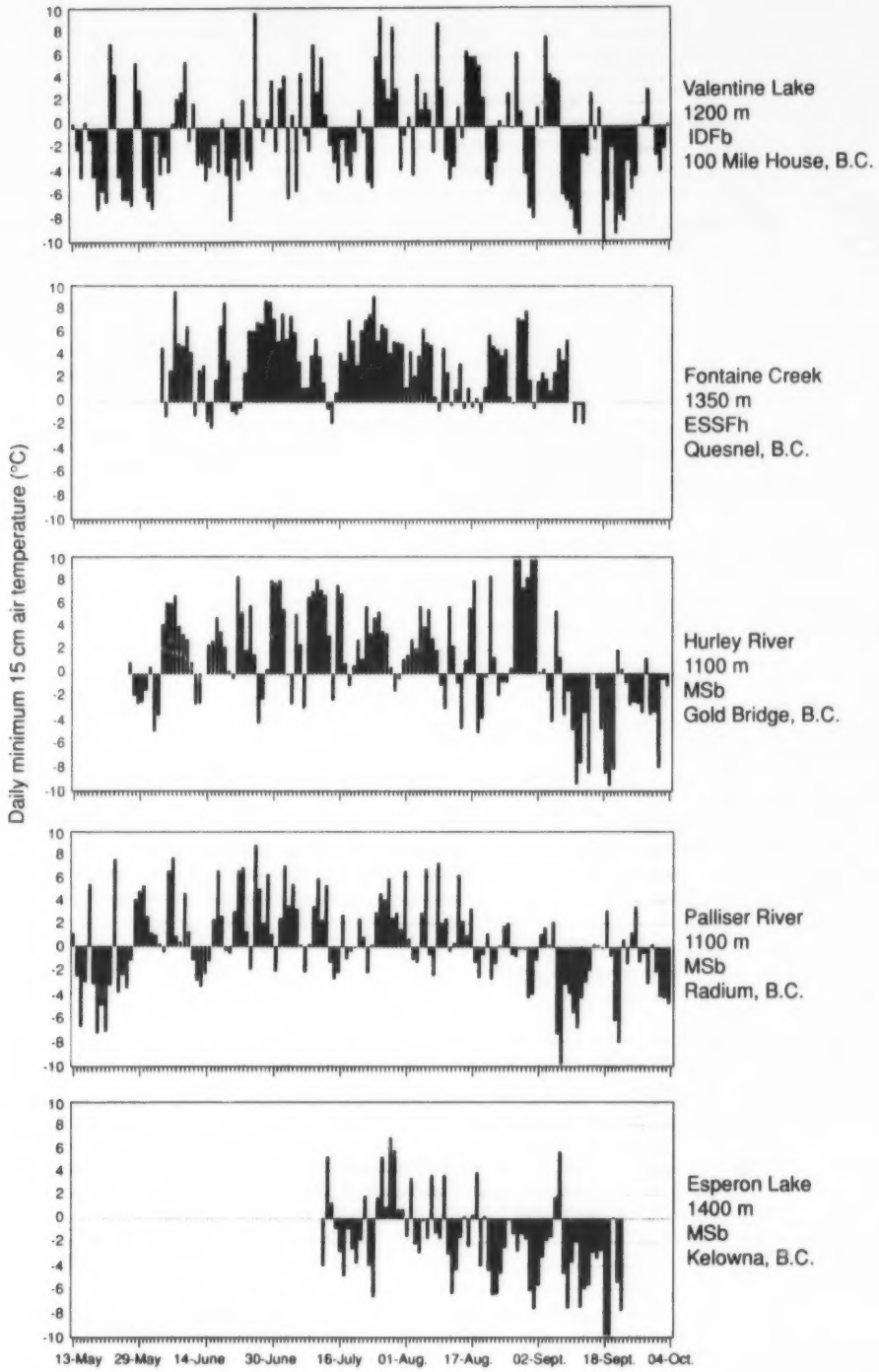

FIGURE 1. Seedling height daily minimum air temperatures in forest clearcuts at 1)Valentine Lake, B.C; 2) Fontaine Creek, B.C.; 3) Hurley River, B.C.; 4) Palliser River, B.C.; and 5) Esperon Lake, B.C.

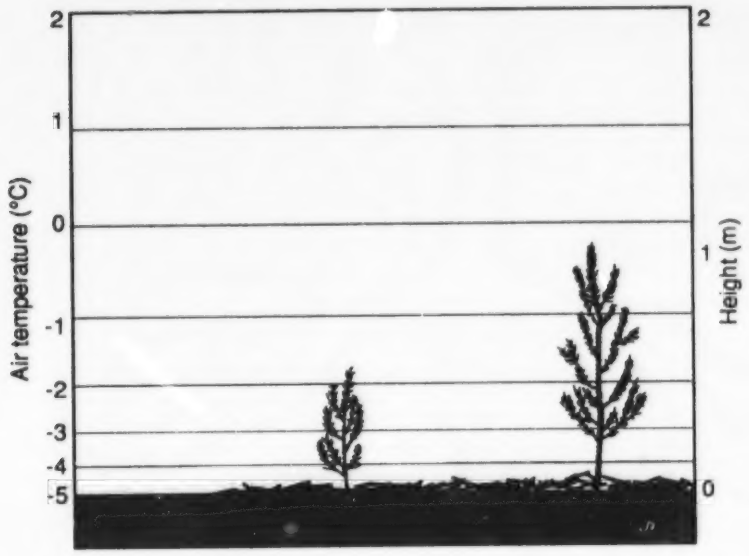

FIGURE 2. Stratification of cold air near the ground surface during a clear, calm night.

TABLE 1. Atmospheric and site-related factors affecting frost occurrence

Factor	Influences
Air temperature	- further heat loss required for freezing to occur. - emittance of longwave radiation from the atmosphere toward the ground surface.
Air humidity	- latent heat content of air. - absorption and emittance of longwave radiation.
Windspeed	- mixing of warmer air toward the ground surface.
Cloud cover	- emittance of longwave radiation from the atmosphere toward the ground surface.
Slope angle	- cold air drainage and accumulation.
Slope position	- size of uphill cold air source.
Aspect	- daily total amount of solar radiation, soil heat storage and time of day when sites are coldest.
Elevation	- air temperature, humidity, cloud cover, windspeed.
Topography	- windspeed, cold air drainage and accumulation.
Vegetation cover	- windspeed, radiative heat loss from the ground surface and soil profile heat storage.
Soil composition	- soil profile heat storage and transfer properties.

2.2 Atmospheric Factors Affecting Frost Occurrence

2.2.1 Longwave radiation

Longwave radiation (i.e., thermal or heat radiation) transfer occurs between surfaces that are at different temperatures. A warm surface radiates more heat than a cool surface, causing a net flow of heat toward the cooler surface. Since the night sky is colder than the ground surface, more longwave radiation is emitted from the ground toward the sky than is radiated from the sky back toward the ground. The net loss of longwave radiation from the ground surface decreases the amount of heat stored there, and as a result, the ground surface temperature drops. This causes heat stored in the soil profile and overlying atmosphere to flow toward the ground surface, which in turn reduces their respective temperatures through the course of the night.

The rate of nocturnal surface cooling is determined by the difference between the rate of radiative heat loss from the ground to the sky and the rate at which heat stored in the soil profile and overlying atmosphere are transferred toward the ground surface. The lowest ground surface temperature that occurs is determined by the difference between the total amount of heat that is radiated from the ground surface toward the sky and the total amount of stored heat that can be supplied to the ground surface from the surrounding soil and atmosphere. The storage and transfer of heat from the air and soil to the ground surface in turn depend on the temperature and windspeed of the overlying air and the temperature, thermal conductivity, and volumetric heat capacity of the near-surface soil.

Soil and vegetation surfaces are almost perfect absorbers and emitters of longwave radiation, and as such, have an emissivity of nearly 1. Longwave radiation is emitted from a perfect emitter (sometimes called a black body) in proportion to the fourth power of its absolute temperature (degrees Kelvin or K) and its emissivity. The atmosphere, in contrast, does not radiate like a simple surface having a uniform temperature. Its temperature varies with height and its emissivity depends on the concentration of atmospheric gases like water vapour, carbon dioxide, and ozone which absorb longwave radiation and re-emit it back toward the surface.

Under cloudy conditions, the concentration of water vapour in the atmosphere is high and the atmosphere absorbs a relatively high proportion of the longwave radiation emitted from the ground surface. As a result, the temperature of a cloudy atmosphere decreases relatively slowly at night. A cloudy sky emits more longwave radiation back toward the ground surface because of its higher temperature and its relatively higher emissivity. This considerably reduces the rate of radiative heat loss from the ground surface, and as a result the ground surface temperature drops relatively slowly.

When the night sky is clear, the concentration of water vapour in the atmosphere is lower and the atmosphere transmits longwave radiation rather than absorbing it and re-emitting it back toward the ground. Consequently, the temperature of the atmosphere decreases quite rapidly, the longwave radiative loss from the ground surface is considerably higher, and the temperature at the ground surface decreases more rapidly.

The rate of longwave radiative loss from the ground to the sky at night can be 5-10 times greater under clear sky conditions than under cloudy conditions. Radiation frosts are, therefore, much more likely to occur on sites where the night sky is clear. Sites in the interior of the province where the air is drier are also more frost-prone than coastal sites where the sky is often cloudier and the air is more humid.

As long as there is a net radiative loss of heat from the ground surface toward the sky, the ground surface temperature can continue to drop. Daily minimum temperatures usually occur just before sunrise. In the spring and fall when the nights are longer, more radiative cooling can occur, and the risk of frost increases. In addition, less heat is stored in the soil and overlying air during the day, further compounding the frost hazard during these seasons.

2.2.2 The physical properties of air

A number of physical properties of air influence the occurrence of radiation and advection frost. Air has a relatively low volumetric heat capacity (ability to store heat per unit volume) compared with water, wood, or soil. Thus, its temperature drops rapidly as it radiates heat. Temperature and humidity are indexes of the amount of heat and moisture stored in air. A parcel of warm, humid air

contains more energy than a similar volume of cold, dry air, so more radiative heat loss is required to reduce its stored heat content and thus lower its temperature to the freezing point.

Air stores energy in the form of sensible heat (heat that can be sensed with a thermometer) and latent heat (heat liberated as the water vapour in the air changes phase to liquid or ice). Only after an excess of water vapour in the air has condensed and frozen onto the ground surface can the air temperature fall below 0°C. If the air above the surface is humid, water will continue to condense on the surface as dew or hoarfrost and in doing so it will release latent heat and maintain the surface temperature near the dewpoint temperature all night. However, if the air above the surface is initially quite dry, very little or no condensation can occur, and much less radiative heat loss is required to cool the surface below the freezing point. Consequently, the risk of radiation frost is greater at sites where the air is initially drier and colder at sunset. It is also one of the reasons why high-elevation sites and areas with dry climates tend to be more frost-prone.

The dewpoint temperature of the air (the temperature at which air would be water saturated, i.e., relative humidity = 100%) during the afternoon is often used to predict the occurrence of frost the following night in agricultural frost risk assessments. When the dewpoint temperature is high, the air contains a lot of energy in the form of the latent heat. When the dewpoint is at or below 0°C, the air contains very little water vapour and frost is likely to occur.

Another important physical property of air is that its density increases as it cools. This causes it to settle near the ground surface. On a flat site, this creates an air temperature inversion which increases the stability of the air layer near the ground. An air temperature inversion reduces the atmospheric turbulence that mixes the warmer overlying air with the air that is radiatively cooled near the surface. A typical progression of nocturnal air temperature profile cooling under calm, clear-sky radiation frost conditions is shown in Figure 3. Notice how the temperature inversion develops upward from the radiatively cooling ground surface throughout the night.

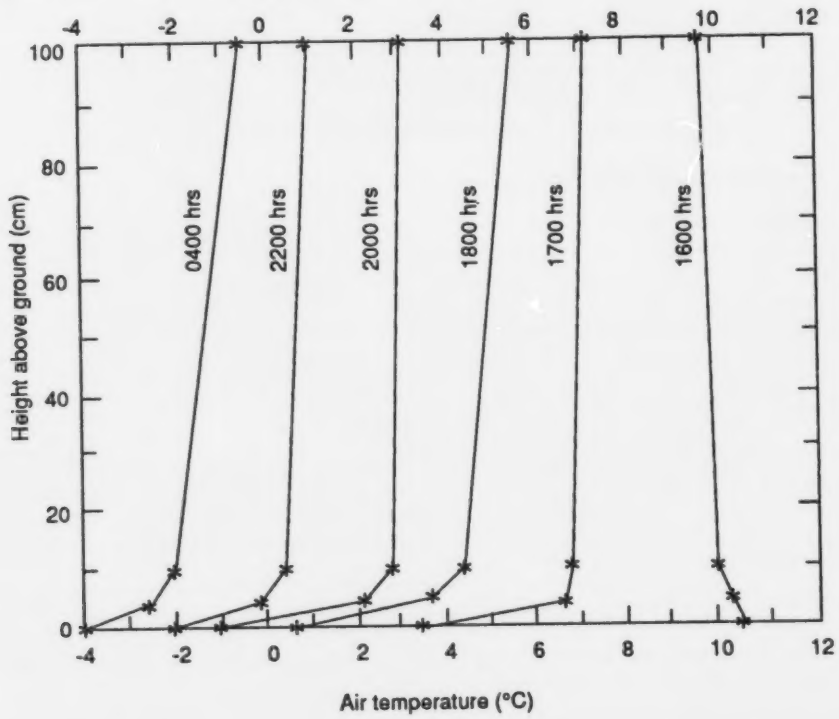

FIGURE 3. A series of air temperature profiles from 1600 hr (before sunset) to 0400 hr, showing the development of the nocturnal inversion under clear, calm weather conditions. (Modified from Leuning and Cremer, 1988.)

The increased density of cold air also causes it to flow downslope, where it ponds to increasing depths in low-lying, stagnant air pools. These areas continue to cool radiatively to form frost pockets. The redistribution of cold air during the night has a significant effect on the occurrence and severity of frost throughout the landscape.

2.2.3 Windspeed

Wind and atmospheric turbulence influence the rate of nocturnal air cooling. Under windy conditions, the radiatively cooled air near the ground surface is rapidly mixed with the warmer air above the surface. This results in a higher surface temperature and a weaker atmospheric temperature inversion. Under very calm conditions, less air mixing occurs, the temperature inversion strengthens, and frost is more likely to occur. Exposed, windy sites are therefore much less likely to be frost-prone than sheltered sites where the windspeed is reduced at night.

An example of how closely coupled the net radiation, surface temperature, and windspeed are during a radiation frost is shown in Figure 4. These conditions were measured in a forest clearcut in the IDFb biogeoclimatic subzone (1250 m above sea level, in level, rolling terrain) near Kamloops, B.C. Dense, 0.2 m tall pinegrass was the dominant vegetation cover on the site. This reduced the windspeed near the ground surface and created a stagnant surface air layer within the grass canopy that was prone to rapid radiative cooling. The pinegrass canopy also acted as a mulch which reduced both daytime soil heat storage and the rate of heat flow from the underlying soil toward the ground surface at night.

During the late afternoon until about 2100 hr, the windspeed at the 1.5 m height was low (<0.6 m/s) and the net radiation was negative (i.e., more longwave radiation was emitted from the ground surface to the atmosphere than was emitted from the atmosphere back toward the ground). As a result, the surface temperature rapidly dropped from about 25 to 6°C. For the next 2 hours the windspeed increased to over 1 m/s, and while the net radiation remained negative (and reached its minimum value), the surface temperature increased by more than 5°C as the warmer overlying air was mixed toward the ground surface. From 2300 hr until sunrise the windspeed decreased to about 0.6 m/s again. This caused the surface temperature to decline slowly from 10 to -3°C. Soon after sunrise the net radiation became positive (as the ground surface absorbed solar radiation), and as a result, the windspeed increased and the surface temperature rose rapidly.

2.3 Site-Related Factors Affecting Frost Occurrence

Elevation, latitude, slope, aspect, topography, surface vegetation cover, and soil composition influence nighttime minimum air temperatures through their effect on wind flow, cold air drainage, air temperature and humidity, soil heat storage, and radiative transfer between the ground surface and atmosphere. Forest harvesting methods, vegetation management treatments, and site preparation treatments can also influence ground surface temperatures through their effect on air flow, radiative heat transfer, and soil heat storage.

2.3.1 Elevation

Elevation influences air temperature and the rate of ground surface radiative cooling. Air temperatures typically decrease by about 0.5 - 0.7°C per 100-m increase in elevation (depending on the water vapour content of the air) because of the decrease in atmospheric pressure with elevation. As a result, at higher elevation sites, less heat loss is required to drop the air temperature to the freezing point at night.

There is also relatively less atmosphere to absorb longwave radiation and re-radiate it back toward the surface at higher elevations (half of the weight of the atmosphere is concentrated in the lowest 5000 m). This, coupled with the lower atmospheric temperature at higher elevations, increases the rate at which the ground surface radiatively cools at night.

Although the rate of nighttime air cooling is faster at higher elevations, not all high elevation sites are equally frost-prone. Local topography predisposes some sites to a higher frost risk where cold air ponding occurs, while at the same time reducing the frost hazard where the cold air is able to drain away to lower elevations.

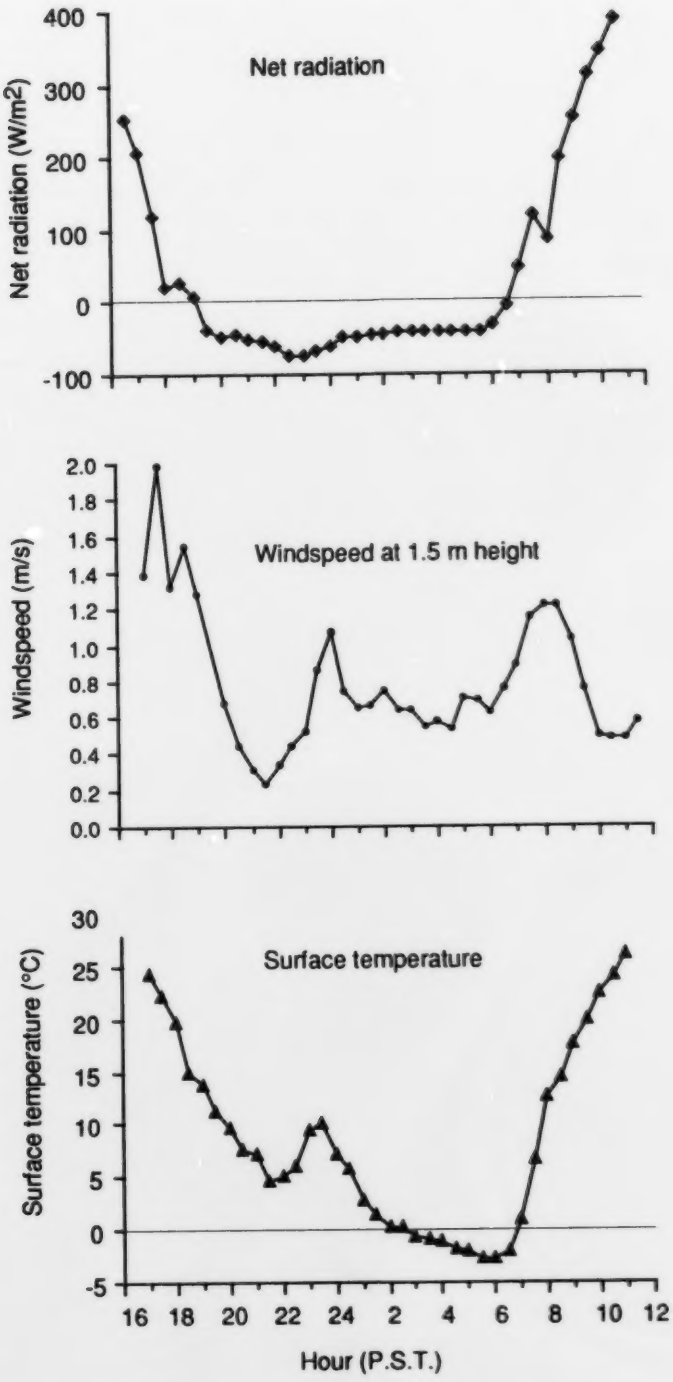

FIGURE 4. The relationship between net radiation, windspeed, and surface temperature under radiation frost conditions in a forest clearcut area (IDFb biogeoclimatic subzone) near Kamloops, B.C.

2.3.2 Latitude

Latitude influences day length. During the early spring and late fall, nights are longer at higher latitudes and so the risk of frost increases during these periods. During the summer the nights are shorter and the frost hazard is reduced. At higher latitudes there may also be an increased risk of cold arctic air masses encroaching during the summer. In general, the risk of frost increases with latitude because colder, drier air and longer nights enhance air cooling near the ground surface. However, many other site-specific factors play a role in redistributing air that is cooled at the ground surface, so not all sites at higher latitudes are equally frost-prone.

2.3.3 Slope, aspect, and topography

Slope, aspect, and topography influence cold air drainage and accumulation. As air cools, its density increases and it settles toward the ground and flows downslope. This downslope air flow is termed katabatic flow. A typical nighttime wind flow pattern in a mountain valley is shown in Figure 5. The air which is radiatively cooled at higher elevations flows down the sides of the valley walls, accumulates in the valley floor, and finally drains down the length of the valley, creating a mountain wind when enough cold air has accumulated to generate a longitudinal air pressure gradient.

A number of physical processes continue to affect the temperature of the air as it flows downhill. A small temperature increase occurs as the atmospheric pressure of the surrounding air increases. This is offset by a small temperature decrease which occurs as the air continues to cool radiatively as it flows downhill. A much more important heating effect can occur as the cold air flow near the surface becomes turbulent and mixes with the warmer overlying air.

The amount of warm air mixing that occurs depends on the rate at which the air flows downhill. This is largely determined by the slope angle and the slope length. On steeper slopes the air cooled near the ground surface is rapidly drained to lower areas. As it flows downslope it is effectively mixed with the overlying air, so a relatively higher ground surface temperature and weaker air temperature inversion develop.

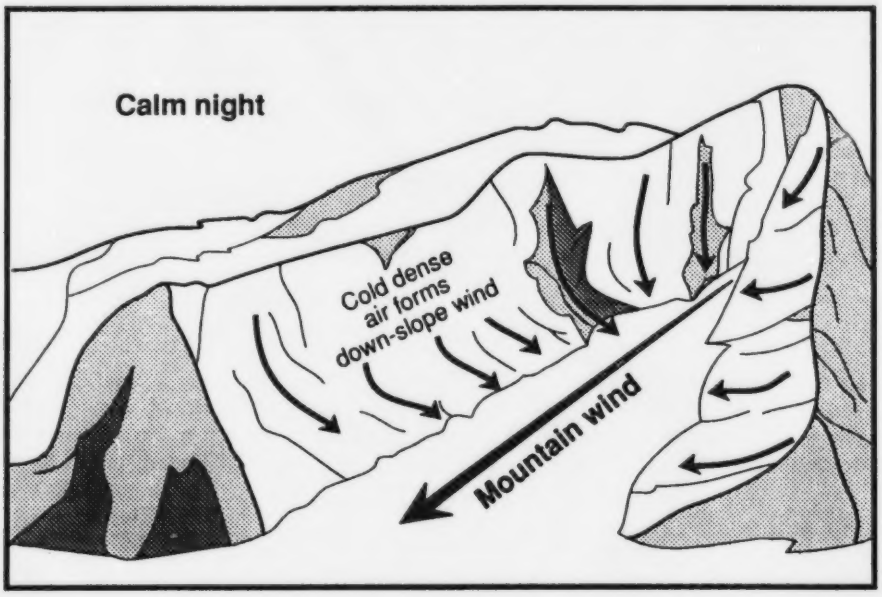

FIGURE 5. A typical nighttime wind flow pattern in mountainous terrain under clear, calm weather conditions.

This effect provides a partial explanation for the reason why seedling height minimum nighttime air temperatures on a high-elevation, sloping clearcut in an ESSFh subzone at Fontaine Creek near Quesnel, B.C. (Figure 1) rarely dropped below -2°C during the summer. Areas on this slope where vegetation or microtopography impeded air drainage caused ground surface temperatures to drop much lower because a considerable amount of frost damage occurred on seedlings and residual trees in sheltered areas.

On more gradual slopes or in gently rolling terrain, the katabatic flow rate is not sufficient to create enough turbulence to mix the overlying air toward the surface. Under these conditions, the dense cold air near the surface remains cold as it flows downslope and is redistributed and concentrated in low-lying areas. There it ponds to increasing depths and continues to cool radiatively, forming frost pockets.

In gently rolling terrain, nighttime minimum air temperatures have been found to be quite well correlated with the height above valley floors, cold air collection basins, and small depressions. By measuring the temperature along transects across a valley basin, Hocevar and Martsolf (1971) found a consistent increase in the air temperature of about 6.2°C per 100-m increase in elevation above the bottom of the basin confining cold air (Figure 6). Laughlin and Kalma (1987) found that the severity of frost was related to topographic position through the effect on cold air drainage and accumulation. On the flat, rolling terrain of the Cariboo plateau, seedling height minimum air temperatures can be more than 10°C higher on knolls than in adjacent small frost pockets under radiation frost conditions (O.Steen, pers. comm., B.C. Forest Service, Cariboo Forest Region).

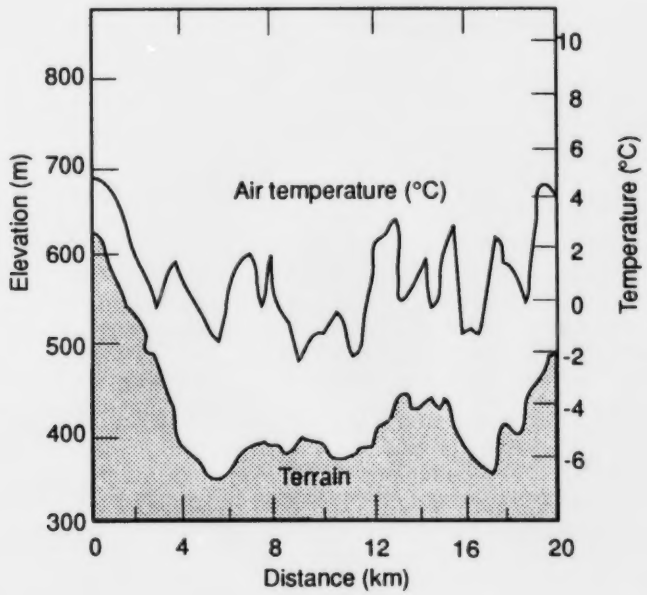

FIGURE 6. Variation in air temperature with distance along a traverse route over hilly terrain during radiation frost conditions, showing the correlation between elevation and temperature. (Modified from Hocevar and Martsolf, 1971).

Bjor and Sandvik (1984) found that nighttime minimum temperatures at the ground surface varied by up to 7°C along a 1.5-km slope (Figure 7). Damaging frosts occurred on the flat terraces where air flow was reduced and cold air accumulated. Temperatures were above freezing on the nearby sloping terrain where the cold air was able to mix with the warmer overlying air and flow downhill.

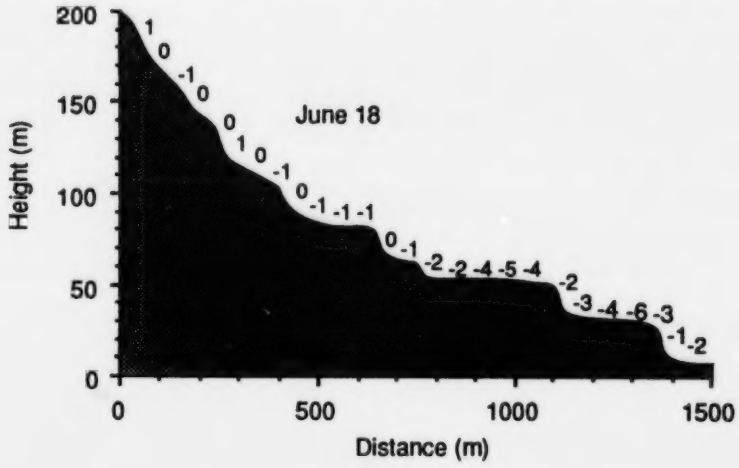

FIGURE 7. Variation in grass minimum temperature along a transect of sloping and terraced terrain. (Modified from Bjor and Sandvik, 1984).

Other features of the landscape also affect the probability of frost occurrence. The size of the cold air source area and the temperature of the air within the airshed significantly affect temperatures in low-lying topographic positions. Aspect influences the amount of solar radiation absorbed by the ground surface during the day. This in turn affects the amount of heat stored in the soil profile that can be conducted back toward the surface and radiated toward the sky at night. As soil profile heat storage increases, surface temperatures can be maintained above freezing for a longer period throughout the night. The frost hazard is, therefore, lower on south-facing slopes and higher on north-facing slopes than on either east- or west-facing slopes.

Although east- and west-facing slopes usually receive the same amount of solar radiation on a daily basis, east-facing slopes generally have a lower probability of frost occurrence than west-facing slopes because of the phase difference in air temperature and solar irradiance. The sun rises earlier in the morning on east-facing slopes and the air temperature remains warmer in the late afternoon because of the thermal inertia of the atmosphere. As a result, east-facing slopes warm up earlier in the morning and cool down only a bit earlier in the evening than west-facing slopes.

A thermal infrared image (Figure 8) of the Moffat lakes area near 100 Mile House, B.C. (at 0300 hr, September 2, 1988) shows the ground surface temperature variation over the landscape under radiation frost conditions. The white regions in the image indicate the occurrence of frost. Ground surface temperatures are above freezing in the darker areas. The effect of topography on cold air drainage and accumulation can be seen by comparing the image with the adjacent topographic map. Cold air drainage down gullies and valleys and cold air accumulation in low-lying areas or on higher elevation flat plateaus is evident. Cutblocks, which appear with distinct linear boundaries, are generally much more frost-prone than the adjacent forested areas. Cold air redistribution within cutblocks, and cold air ponding near the lower cutblock boundaries which act as air dams, are also evident.

2.3.4 Vegetation cover

A vegetation canopy influences radiative exchange between the ground surface and the atmosphere, windspeed, cold air drainage, mixing of cold surface air with warmer overlying air, and soil profile heat storage. Vegetation can either have a beneficial or detrimental effect on the occurrence of frost, depending on its height, structure, and density.

A vegetation canopy decreases the net radiative loss from the ground surface to the atmosphere by absorbing and re-emitting some of the heat radiated upward from the ground. Instead of radiating heat at a rapid rate to the cold night sky, the ground radiates more slowly toward a relatively warm

vegetative canopy, which in turn re-radiates some of this heat back toward the surface. The amount of canopy cover above the ground surface consequently affects the rate of radiative heat loss.

FIGURE 8. A topographic map and thermal infrared image (at 0300 hr, September 2, 1988) (scale = 1 to 100 000) of the terrain surrounding the Moffat lakes in the Cariboo Forest Region, B.C. The white areas in this image indicate ground surface temperatures below 0°C. The darker areas are above 0°C. Cutblock areas are defined by the sharp boundaries on the image. (Steen. FRDA Research Project 3.65, B.C.F.S.)

Vegetation cover also decreases the windspeed at the ground surface and can create a layer of still air that is prone to radiative cooling. The height and density of the vegetation influences the windspeed and air mixing within the canopy. A dense canopy tends to reduce the windspeed uniformly near its upper surface, creating a stagnant layer of air underneath that is not as well mixed with the overlying air. A sparser canopy allows the wind to penetrate deeper, permitting turbulent gusts to mix the warmer overlying air with the cold air near the ground surface.

The height and density of vegetation also affect the amount of heat that is stored in the soil profile during the day. A dense canopy that shades the ground surface reduces soil profile heat storage. Soil heat conducted toward the ground surface at night keeps the surface temperature from dropping as rapidly. Heat stored within the vegetation canopy itself is also liberated at night. However, this heat reservoir is usually small compared with the total amount of heat radiated from the ground to the atmosphere throughout the night.

The height and density of vegetation cover have a number of complex and interacting effects on the rate of surface cooling. Different types of vegetation cover can significantly affect the nocturnal cooling rate and, as a result, predispose the ground beneath various canopies to different levels of frost risk.

A tall, closed canopy of trees reduces the frost hazard by reducing the net radiative loss from the ground surface. The radiating foliage near the top of a tall canopy is heated by the surrounding air, which is usually well mixed and warmer than the air near the ground. Sparse, short herbaceous or shrub canopies can also reduce radiative heat loss from the ground by replacing portions of the cold sky with relatively warmer foliage. However, short canopies are not as effective as taller canopies that have higher foliage temperatures and that block more of the seedlings' view of the cold sky.

A low, dense grass canopy can be a frost-prone environment for seedlings. The grass creates a stagnant air layer that traps cold air and allows it to continue radiatively cooling. The coldest layer within the grass canopy is not at the ground surface, but nearer the densest layer of vegetation where more longwave radiative loss occurs (Figure 9). Removing the grass canopy reduces the frost hazard for seedlings by increasing the mixing of cold air near the surface with warmer overlying air, and eliminating an insulating canopy layer which traps and holds cold air. In addition, removal of the grass exposes the soil surface and increases heat storage in the soil profile during the day so that more heat can be radiated from the soil surface toward the seedling at night.

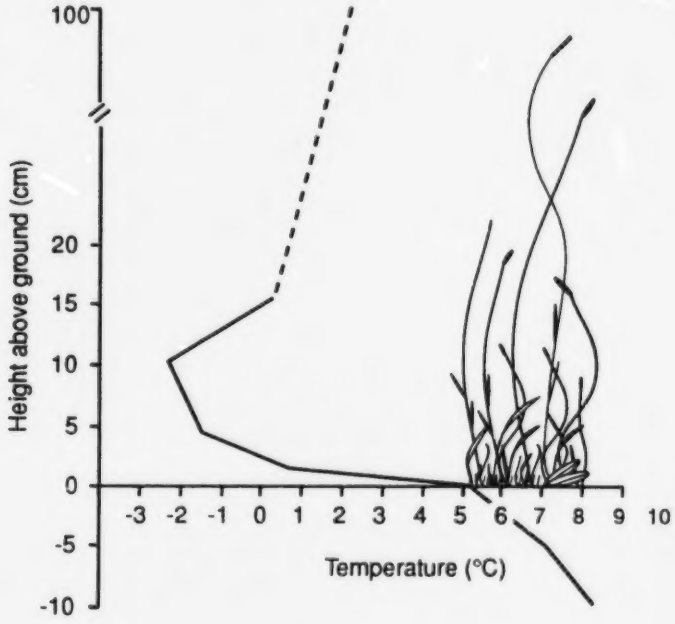

FIGURE 9. A vertical temperature profile in an alpine pasture at 0400 hr in late August. The lowest temperature occurs at the surface of the densest vegetation layer. (Modified from Sakai and Larcher, 1987.)

3 EFFECT OF SUMMER FROST ON CONIFER SEEDLINGS

3.1 Frost Resistance

Frost resistance is the ability of a plant to withstand frost without being physiologically or morphologically damaged. Conifers have adapted to survive freezing temperatures by either tolerating the presence of ice in their tissue or by avoiding ice formation within the tissue by the process of supercooling (Kramer and Kozlowski 1979). In the supercooled state, water within the cell remains liquid, yet is below 0°C because of the presence of solutes (e.g., sugars and proteins) which lower the freezing point. Frost resistance is determined by both the frost tolerance and frost avoidance mechanisms used by the plant (Larcher 1985).

The frost resistance of conifers varies considerably throughout the year. In the summer, frost avoidance (by supercooling) is the primary frost resistance mechanism (Glerum 1985). During the fall and winter, frost tolerance increases as hardening occurs. Conifer needle, stem, and root tissues show a marked difference in seasonal frost tolerance, as shown in Figure 10.

Although specific frost resistance levels for most conifer species growing in British Columbia have not been well established, there is evidence to suggest that temperatures lower than -3 to -5°C during the

growing season can cause tissue damage in many species. Rapid tissue cooling, longer exposure to low temperatures, and an increased frequency of frosts during the growing season all increase the degree of frost damage.

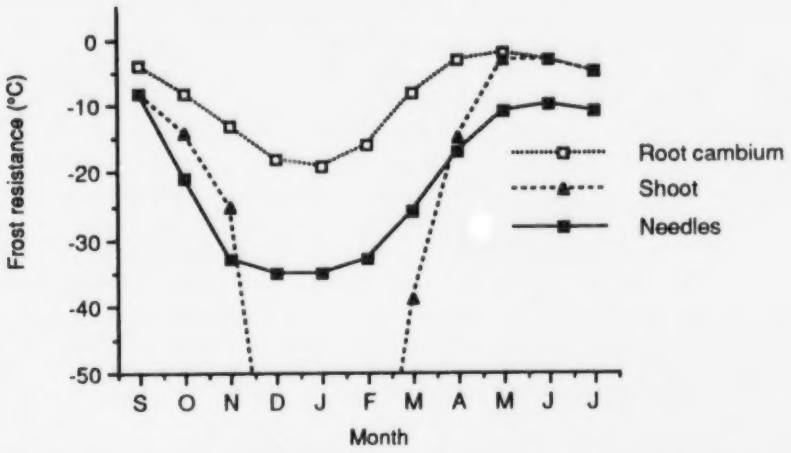

FIGURE 10. The annual variation of frost resistance of needles, shoots, and roots in *Abies alba*. Tissue damage occurs at temperatures lower than indicated by these points. (Modified from Larcher 1985.)

3.2 Mechanisms of Frost Damage

Two distinct types of frost damage are thought to occur in conifer seedlings exposed to low temperatures during the summer. In one case, the water surrounding the plant cells supercools (the water temperature drops below 0°C but ice does not form) to the ice nucleation temperature. At this temperature, minute particles (ice-forming nuclei) in the extracellular water cause it to freeze. Depending on the rate and duration of freezing, this may or may not cause cell mortality.

When ice forms outside the cell wall, a very strong water potential gradient (or difference in water potential) is created between the water inside and outside the cell. This causes water to flow from inside the cell toward a growing ice lens between cells. As the water content within the cell decreases, the cell membrane shrinks inward, away from the more rigid cell wall. As freezing continues, cell dehydration progresses until the cell membrane separates from the cell wall. Physical damage to the cell membrane may prevent the cell from regaining internal pressure as the tissue rehydrates. Rupturing of cell membranes can also cause biochemical damage, which affects physiological processes. These effects can be localized within the plant, and though they may not necessarily cause mortality, they can cause enough stress to affect plant water relations, or rates of respiration and photosynthesis within affected tissues.

The second type of frost damage is lethal and is thought to occur when the water within the cell freezes. This occurs when the intracellular water temperature drops to the ice nucleation point. The ice nucleation temperature depends on the solute concentration of water and the presence of ice-forming nuclei. Pure water can be supercooled to about -40°C before spontaneously freezing. However, intracellular substances (primarily sugars, starches, and ice-nucleating active bacteria) usually cause freezing to occur at temperatures above -7 to -10°C during the active growing season (Weiser 1970).

There are a number of possible methods of decreasing the ice nucleation temperature of water in plant tissues, but they have not yet been found to be effective in conifers. Certain chemicals, such as plant growth regulators, have been effective for some plants. Inoculation of foliage with non-ice nucleating active bacteria, or use of antibiotics that control ice-nucleating bacteria, has also been successful with some species. The selection and cloning of phenotypes that are more frost-resistant may be a more practical and effective method of improving conifer stock quality.

3.3 Frost Damage Symptoms

Frost damage to seedlings typically occurs on the current year's foliage, particularly on the terminal leader and on laterals that are directly exposed to the cold night sky. Older foliage is apparently more frost-resistant, though it can suffer damage from more severe frosts.

Frost damage symptoms are quite easy to identify. They usually begin to appear within a few days after a frost occurs and are usually fully developed within 1-2 weeks (Glerum 1985). The symptoms appear as browning, chlorosis, or necrosis of current year's foliage and active growing points. The terminal shoot often curls slightly. Sometimes these symptoms can be confused with water stress damage in older foliage, particularly in pine.

Either partial or total needle damage can occur. Sometimes only the outer exposed portions of the needles and the terminal shoot tip show damage. Often, whole shoots are affected. Damaged needles and shoots can remain on the seedling for many weeks before abscission occurs. Dead, defoliated frost-damaged shoots can remain on the seedling for a number of seasons after the damage occurs.

Damage to the terminal shoot usually causes growth to be redirected to the lateral shoots. As a result, older seedlings or saplings develop a bushy growth form if they are repeatedly frost-damaged over the years. Often the crowns appear rounded and the foliage becomes denser, similar in appearance to damage caused by animal browsing. Sometimes the branches are devoid of foliage and the bark can be thickened or calloused.

There is some evidence to suggest that succulent new needles that do not have a well-developed cuticle are more prone to frost damage than older needles (Sakai and Larcher 1987). Healthy, vigorous seedlings have also been observed to be more prone to summer frost damage. The mechanism for this may be related to larger cell size and higher tissue water content. Seedlings that osmotically adapt (raise their intracellular solute concentration) in response to increasing levels of water stress during the growing season may have a lower risk of being damaged by frost.

Lundmark and Hallgren (1987) found more pronounced frost damage in seedlings exposed to full sunlight after a frost. They suggested that the photo-oxidation of chlorophyll and subsequent photo-inhibition of photosynthesis caused this damage. A vegetation canopy that partially shades the seedling foliage should reduce this type of damage.

There is also evidence to suggest that considerable sublethal frost damage can occur without the seedling exhibiting visible symptoms. Sublethal damage of cell membranes, organelles, xylem elements, and root tissue has been found to affect seedling photosynthesis and transpiration rates significantly (DeLucia and Smith 1987). As a result, growth rates of frost-damaged seedlings are usually considerably reduced. The seedling may also be much more susceptible to other environmental stresses after sublethal frost damage has weakened it. Frost can cause tissue damage which is ultimately manifested as slow starvation or water stress. More research is still required to identify, precisely, the effects of frost damage on conifer seedlings, particularly the sublethal effects.

4 OPERATIONAL STRATEGIES FOR SUMMER FROST

4.1 Principles of Frost Protection

A crop can be protected against frost using methods based on consideration of: (a) site selection, (b) longwave radiation interception, (c) thermal insulation, (d) air mixing, (e) direct convective air heating, (f) radiant heating, (g) release of the heat of fusion of water, and (h) soil and ground cover manipulation. Many of these methods , because they require active management, have a high initial capital cost, or require an energy supply, are only economically feasible for high value crops.

Given the economic constraints imposed in forest management, only the more passive frost protection techniques can be considered. Though often not as effective as active frost management practices (where wind machines, radiant heaters, fog generators, smudge pots, or spray irrigation are used), passive frost management techniques can reduce the risk of frost for seedlings in many types of sites throughout the interior of the province.

Passive frost management involves the use of methods that reduce the frequency or severity of frost without using additional energy sources during actual frost events. To be effective, the frost resistance of the crop tree species and the frequency and severity of frosts which occur at the site must be considered. There is still not enough information about the frequency and severity of frosts that detailed passive frost management guidelines can be implemented for the forest land in the province. This situation is improving, however. Climate data from forestry research projects throughout the Interior have increased the understanding of frost occurrence and severity on a wide range of sites. A study is also presently under way to identify frost-prone areas in the Cariboo Forest Region (O. Steen, FRDA Research Project 3.65, "Frost-Prone Sites in the Central Interior Plateau").

Much of what is already known about frost occurrence and resistance can be directly applied in regenerating forests. As more experience is gained in identifying frost-prone sites, and as the effectiveness of site preparation and vegetation management treatments are assessed over a wider range of environments, more detailed frost risk guidelines can be implemented at the pre-harvest site prescription stage.

4.2 Identifying Frost-Prone Sites

Identifying frost-prone sites is an important aspect of frost risk management. With the application of what is already known about the principles that govern the causes and occurrence of frost, it is possible to use landscape identifiers such as slope, aspect, elevation, and topography to classify frost risk at a fairly large scale. The assessment of frost risk at an individual site can then be improved by examination of site-specific characteristics in more detail. An understanding of the effect of terrain and microtopography on cold air drainage and accumulation should help determine where potential frost problems are most likely to occur. Site-specific identifiers such as the presence or absence of certain plant species in nearby areas can help delineate frost-prone areas. Examination of similar adjacent plantations for signs of frost damage may also provide important clues as to the severity of the frost hazard in an area. Thermal images, such as shown in Figure 8, can also be used to map high risk areas. There is still much to be learned about the occurrence of frost. Many refinements will occur as the problem is examined in relation to frost hazard for regenerating seedlings.

From the summary of principles outlined above, some preliminary guidelines for identifying frost-prone sites are outlined below.

a. Climatic regime

Drier biogeoclimatic subzones or areas where frequent clear skies occur at night are at increased risk. High rainfall areas are at lower risk.

b. Elevation

High-elevation sites are at high risk because of the relatively higher rate of ground surface radiative cooling. Frost damage has been observed on sites above 1000 m on sites throughout the Interior. Emmingham (1985) cautions that damaging frosts occur in Oregon at elevations as low as 650 m under certain topographic conditions. Not all high-elevation sites are equally frost-prone. Cold air drainage can decrease the risk on some sites, just as it can increase it on others.

c. Topography

Areas where cold air drainage accumulates or where cold air flow is obstructed or slowed are at high risk. Areas beneath large high-elevation airsheds are also at an increased risk. Mid-slope benches, valley bottoms, gullies, bowls, basins, and other low-lying terrain where cold air collects are examples of higher risk areas. Flat or gently rolling plateaus where air flow is slow or cannot readily drain away are also at high risk. Slopes greater than about 10-15 % appear to be at lower risk because of increased air movement. Exposed, windy ridges and mid-slope positions where cold air is able to drain away are also at a lower risk. In gently rolling, flat terrain the small knolls are at a lower risk than the surrounding hollows where cold air ponds. Similar principles apply at the microtopographic scale. Small hollows and depressional areas collect cold air and can increase the risk of frost damage in individual planting spots.

d. Aspect

South-facing slopes may have a lower frost risk and north-facing slopes may have a higher frost risk than either east- or west-facing slopes. This effect should be less pronounced in the summer than in the spring or fall when aspect has a greater influence on solar irradiance, particularly at higher latitudes.

e. Vegetation cover

Seedlings growing under tall, dense vegetation canopies appear to be at a lower frost risk. Low, sparse herbaceous or shrub canopies may also provide some benefits. Dense grass cover has been found to increase the frost risk.

Vegetation can also obstruct air flow. Abrupt changes in vegetation height within cutblocks or cutblock boundaries can dam cold air and create areas of higher frost risk.

f. Forest harvesting

Adjacent cutblocks can act as sources of cold air. Cutblock boundaries should be laid out to enhance air flow where possible.

4.3 Site Preparation Treatments to Minimize Frost Damage

Site preparation treatments that are commonly used in clearcuts to improve planting access, increase seedling root zone temperatures, conserve water, and control competing vegetation can also effectively reduce the risk of summer frost.

The passive frost protection techniques that have been found to reduce the frequency and severity of frost involve treatments which: (a) increase mixing of the warmer overlying atmosphere with the cold air generated at the ground surface; (b) reduce cold air ponding near the ground surface; (c) absorb and re-radiate longwave radiation emitted from the ground surface; or (d) increase daytime heat storage and nighttime heat release from the soil profile and vegetation canopy. Site preparation treatments that impart as many of these frost prevention mechanisms as possible are the most effective.

On some sites, site preparation treatments are not sufficient to prevent frost. For example, in deep frost pockets that have a continuous supply of cold air throughout the night there is probably no passive frost management site preparation treatment that is likely to be effective.

Site preparation treatments that allow warmer overlying air to mix toward the surface and increase air flow around the seedling probably confer the most frost protection. It apparently does not take much of an increase in ventilation near the ground to reduce the risk of frost (e.g. see Figure 4).

Conventional site preparation treatments such as burning, scalping, trenching, mounding, and ripping have been found to decrease the risk of radiation frost damage to conifer seedlings on sites where frequent summer frost occurs.

Scalping off the surface organic horizons decreases the risk of frost (Black *et al.* 1988). Surface organic material has a low thermal conductivity and volumetric heat capacity and, as a result, gets much colder than a mineral soil surface at night. Scalping provides the added benefit of conserving water by reducing the evapotranspiration rate in drought-prone areas. However, it may lead to nutritional problems. The size of scarified patch required to produce the desired increase in ventilation has not been examined in detail. Observations of conifer damage in failed plantations suggest that something larger than a small hand-screef is probably required on level land, although a small amount of disturbance may be adequate on sloping terrain where the risk of frost is lower.

Ripping the soil to break up and remove the vegetation cover and incorporate the organic surface horizon will increase daytime soil heat storage and nighttime heat release. It should also increase cold air mixing. Hall (1985) found that ripping reduced frost damage. Bjor and Sandvik (1984) found that plowing increased minimum night temperatures by up to 4°C on frost-prone sites in Norway.

Steep-walled trenches, 0.2-0.3 m deep, created with ripper teeth, have been found to reduce seedling frost damage on drier IDF sites. Trenching reduces the cold layer of air near the ground by removing vegetation cover; reduces longwave radiation to the sky by decreasing the amount of cold night sky seen by the seedling; and increases the soil surface area for heat flow from the soil toward the seedling at night. The wall steepness and depth of the trench determine its effectiveness (Geiger 1950). Shallow trenches are not as effective as deep trenches with steeper walls, and can act as small frost pockets where cold air tends to pond.

Mounding can decrease the frequency and severity of frost by creating a mineral soil microsite that is raised above the surrounding terrain where more turbulent air mixing occurs. Larger mounds may be more effective than small mounds. Large mounds, such as those created by a dip and dive cat blade treatment on a slope, can create small frost pockets that trap cold air, so care must be taken to ensure that the seedling is planted on a part of the mound where cold air can drain away.

Planting in microsites which reduce the amount of cold sky seen by the seedling (its sky view factor) or radiate heat back toward the seedling at night (such as near large stumps, beside fallen logs, or in soil screefs) can also reduce the frost hazard in sites with poor air drainage. Low-lying planting spots that collect cold air should be avoided in very frost-prone sites.

The effect of trenching, scalping, and mounding on daily minimum seedling height temperatures in a clearcut in the Esperon Lake area near Kelowna, B.C. (MSb biogeoclimatic subzone, 1400 m elev.), is shown in Figure 11. The clearcut had been recently site-prepared by burning and very little vegetation had re-established. The burned area had a 15 cm deep surface organic horizon, the scalp was a 50 cm diameter mineral soil patch, the steep-walled trench was 30 cm deep, and the mineral mound was 30 cm in diameter and 20 cm high. The burned treatment showed the greatest diurnal fluctuation in seedling height air temperature and the lowest minimum temperature because of the low thermal conductivity and volumetric heat capacity of the organic surface horizon. Exposing mineral soil by scalping, trenching, and mounding typically increased the nighttime minimum air temperatures by up to a few degrees. On the night shown in Figure 11 these treatments increased air temperatures from a damaging frost of -6°C to a more tolerable -3°C. In an adjacent low-lying area where cold air accumulated, these site preparation treatments were not as effective. More research is still required to determine the effectiveness of site preparation and vegetation management treatments on sites with different frost hazards.

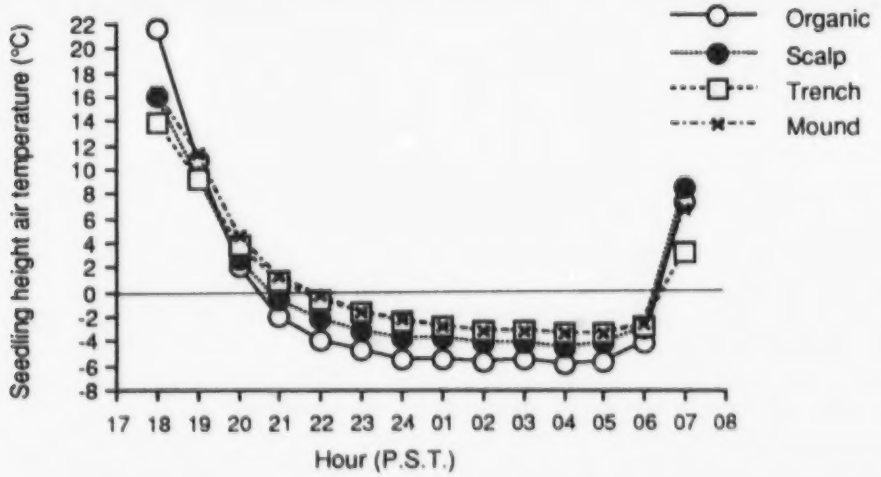

FIGURE 11. Seedling height air temperatures in a forest clearcut in the Esperon Lake area (MSb) near Kelowna, B.C. under typical summer radiation frost conditions. The burned area had a 15 cm deep surface organic layer, the scalp was a 50 cm diameter mineral soil patch, the steep-walled trench was 30 cm deep and the mineral mound was 30 cm in diameter and 20 cm high. (Stathers. FRDA Research Project 3.42)

4.4 Harvesting Methods to Minimize Frost Damage

Harvest methods can regulate the flow of cold air over the landscape. Nighttime air flow and drainage pathways through cutblocks should be examined for barriers that obstruct air flow and create frost pockets. Cutblock boundaries, particularly at the lower edge of clearings, often act as cold air dams. Cold air redistribution within cutblocks is evident in the thermal image shown in Figure 8. Designing cutblock boundaries to allow cold air to drain away to lower sites can significantly reduce the frost hazard. Opening air drainage pathways to enhance air flow between successive clearcuts should also be considered where possible. The openings probably do not have to be too wide, but should be located in the lowest terrain where cold air accumulates. Since cutblocks often act as cold air sources, the sequence in which cutblocks are harvested can also affect regeneration in adjacent areas.

Different harvesting methods can create different seedling microclimates. In frost-prone areas where site preparation treatments cannot provide adequate frost protection, alternatives to clearcutting might be necessary to regenerate a desired species that is prone to frost damage. Maintaining or modifying the structure of the forest canopy to take advantage of the reduction in longwave radiation loss from the ground surface at night can considerably reduce the frequency and severity of frost as shown by Hungerford and Babbitt (1987) in Figure 12. During the whole year, only 24 frost-free nights occurred in the clearcut, while in the adjacent uncut and shelterwood areas there were more than 113 frost-free nights. Regeneration problems were recurrent in the clearcut, but not in the other treatments because of the reduced frost hazard.

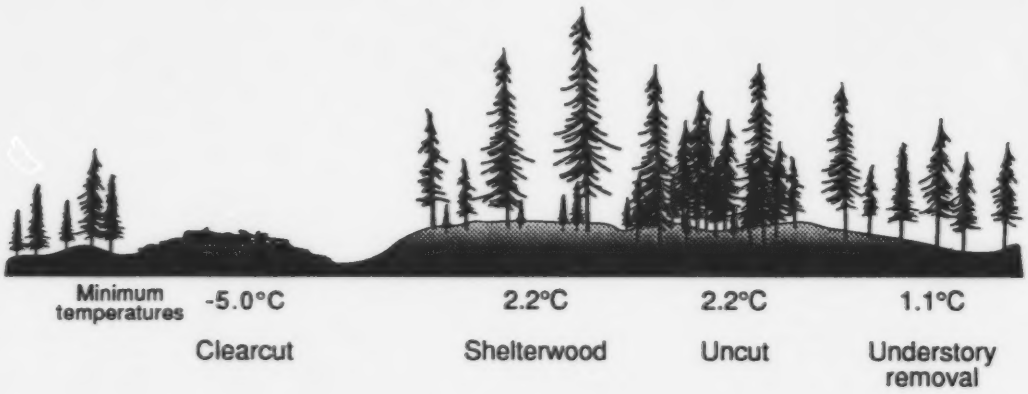

FIGURE 12. Daily minimum ground surface temperatures for various overstory cutting treatments at Lubrecht, Montana, on August 29, 1978. (After Hungerford and Babbitt, 1987.)

A number of Scandinavian studies have also reported the use of shelterwoods or nurse crops to protect spruce regeneration from frost (Bjor and Sandvik 1984; Odin *et al.* 1984; Leikola and Rikala 1983) report better spruce seedling growth beneath a dense nurse crop in a frost-prone area.

Spruce and Douglas-fir stands often develop in the understory of young lodgepole pine stands in the interior of British Columbia. The microclimate created in the understory of the pine stands is much better suited to the regeneration requirements of both spruce and fir than is the harsher clearcut environment. A comparison of seedling height daily minimum air temperatures through the growing season in a clearcut and adjacent spaced lodgepole pine stand (approx. 700 stems per hectare, 6 m tall, 50% canopy cover) in the IDFb biogeoclimatic subzone at Valentine Lake near 100 Mile House, B.C., is shown in Figure 13. Daily minimum temperatures under the spaced stand were typically 2 - 4°C higher than in the clearcut. Between June 1 and September 1 there were 33 frosts below -3°C in the clearcut, but only 3 frosts of that severity in the stand.

In frost-prone areas where clearcutting is desired or necessary it may be possible to create small clearings of a few tree heights or less in diameter to minimize the sky view factor and thus reduce radiative heat loss and ground surface temperatures at night (Cochran 1969). Successive narrow strip clearcuts

can also be used to decrease the night sky view factor, but they must be designed to allow cold air drainage. Odin *et al.* (1984) have found that mechanically cutting 2.5 m wide corridors through dense, low deciduous stands also provides frost protection for conifer seedlings.

Recommending an optimum residual shelterwood or partial cut canopy crown cover that will provide adequate frost protection for frost-prone sites is difficult. It is likely to vary considerably, depending on the severity of frost and whether the frost is typically generated by radiative cooling or by cold air advection and ponding. It also depends on the height, density, and crown form of the stand. Odin *et al.* (1984) examined the effect of residual canopy density in low, dense birch shelterwoods with small crowns and found that a spacing of at least 2 x 2 m was required to produce a noticeable nocturnal warming effect, and an even closer spacing was necessary to provide adequate frost protection. Nunez and Sander (1982) found that Eucalyptus shelterwood canopy covers of about 50% reduced the nighttime net radiative loss by about one half and increased air temperatures within the canopy by up to 4°C. A similar response can be seen in Figure 13 for a conifer canopy cover of about 50%. In all likelihood, a residual crown cover

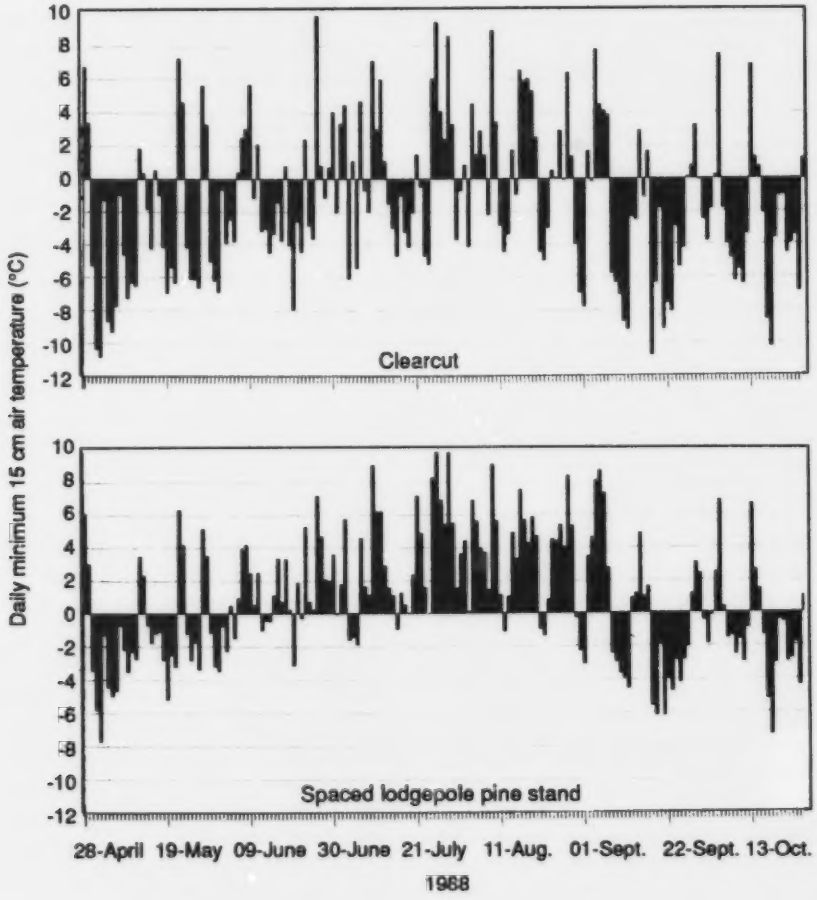

FIGURE 13. A comparison of seedling height daily minimum air temperatures in a forest clearcut and adjacent spaced lodgepole pine stand in the IDFb biogeoclimatic subzone at Valentine Lake near 100 Mile House, B.C. (Sutherland. Unpublished data. Cariboo Forest Region)

of about 50% is probably necessary to significantly reduce the occurrence of severe nighttime radiation frosts under most young conifer stands. Emmingham (1985) recommends that residual basal areas of between 80 and 120 ft^2 are necessary to promote regeneration beneath shelterwoods in frost-prone areas in Oregon.

4.5 Implications for Planting Stock

There are a few management options that can currently be used to decrease the risk of frost damage or increase stock hardiness. Selection of provenances which are better suited to colder conditions during the growing season may provide an adequate solution to frost problems on some sites. Lodgepole pine is thought to be able to withstand growing season temperatures down to -8 or -10°C, whereas Engelmann spruce and Douglas-fir have been found to suffer severe frost damage at temperatures of -3 to -5°C (Gusta 1983; Glerum 1985; Christersson 1971). These frost resistances probably vary by many degrees within each species, depending on provenance, seasonal climatic conditions, stock quality, and a number of other factors. The relative frost resistance and shade tolerance of common tree species found in British Columbia are shown in Table 2.

TABLE 2. Relative frost resistance and shade tolerance of common tree species in B.C.

	Shade Tolerance		
Frost resistance	**Intolerant**	**Moderately tolerant**	**Highly tolerant**
High	Lodgepole pine Trembling aspen Black cottonwood	White pine Black spruce Engelmann spruce	Mt. hemlock
Moderate	Ponderosa pine Western larch	Noble fir	Subalpine fir Sitka spruce Pac. silver fir Grand fir
Low	Red alder	Douglas-fir	Western hemlock Western redcedar

On sites where environmental conditions are more extreme and repeated plantation failures have occurred because of frost damage, a change of species may be required. In very high risk areas, harvest methods which reduce the frequency and severity of frost should be considered.

The time of planting and the condition of the stock at the time of planting also affect frost hardiness. Seedling phenology has an influence on frost tolerance. If the annual rhythms of various physiological processes that occur in seedlings are interrupted or delayed, the susceptibility to frost damage can increase.

Cold-stored 1+0 styroplug Engelmann spruce seedlings are usually planted on higher elevation ESSF sites in the southern and central interior regions of the province in late June and July because of poor access or a late melting snowpack. These seedlings normally flush within a few weeks after being planted (often many days after natural regeneration on the site flushes), but since the growing season is short on these sites they are often not able to complete their growth cycle and harden adequately before the end of the summer. As a result, they often suffer severe frost damage late in the summer.

One potential solution to this problem which has shown mixed initial results involves hot-planting (2+0) stock that has already set a bud (A.Vyse, pers. comm., B.C. For. Serv., Kamloops Forest Region, Sept. 1988). In this hardened condition the foliage is not as susceptible to frost damage. The summer planting also enables the tree to grow roots in the fall and to adjust phenologically so that it has a better chance of adapting to the environmental conditions that occur in the next growing season.

Consideration should also be given to planting a mix of species within cutblocks that have a range of frost hazards. Engelmann spruce is normally planted in the wetter low-lying areas within a cutblock. However, it is often severely frost damaged or killed in these areas because of the high frost hazard. Lodgepole pine is a more suitable species for these conditions because, though it grows slowly, it usually survives.

There are currently no known nursery cultural practices that can be applied to seedlings to confer increased frost resistance for more than one season after outplanting. The proper selection of species or provenance and the use of good quality stock are, therefore, very important for successful plantation establishment in frost-prone areas.

4.6 A Framework for Frost Management

A frost management strategy can be implemented by:

1. identifying frost-prone sites.
2. assessing or estimating the severity of the frost hazard at the site.
3. determining whether cold air drainage modifications can reduce the frost hazard.
4. selecting site preparation or vegetation management treatments that can reduce the frost hazard.
5. changing to a more frost-resistant stock type, provenance, or species.
6. changing to a harvest method that provides more frost protection on very high risk frost sites.

Local knowledge, acquired experience, and further research will improve the implementation of these preliminary frost management guidelines.

5 GLOSSARY OF TERMS

ADVECTION - used to describe predominantly horizontal movement in the atmosphere.

ADVECTION FROST - frost caused by advection of cold air.

BLACK BODY - a surface that absorbs and emits radiation (i.e., it does not reflect or transmit radiation). Its emittance is proportional to the fourth power of its absolute (Kelvin) temperature.

BOUNDARY LAYER - a thin layer of air adjacent to a surface.

CELL TURGOR - internal cell pressure.

CONDENSATION - the process whereby a vapour changes phase to a liquid and releases heat.

DEWPOINT - the temperature to which a given parcel of air must be cooled for the relative humidity to reach 100%.

EMISSIVITY - the ratio of the total radiant energy emitted per unit time per unit area of surface (at a specified temperature and wavelength) to that of a perfect emitter (black body) under the same conditions.

EMITTANCE - longwave radiation is emitted by a surface in proportion to the fourth power of its absolute temperature (degrees Kelvin or K).

EXTRACELLULAR - (or intercellular) between cells.

FLUX - the rate of flow of a quantity. (e.g., J/s = W)

FLUX DENSITY - the flux per unit area. (e.g., W/m^2)

FROST - the condition that occurs when the surface temperature of the ground or a plant drops below 0°C. The term is also used to describe the icy deposits which may form on a surface under such conditions (e.g., hoarfrost or glaze).

FROST-FREE PERIOD - the number of days between the last frost in the spring and the first frost in the fall.

FROST POCKET - a low-lying area where stagnant cold air accumulates at night.

FROST RESISTANCE - the ability to withstand frost without causing physiological or morphological damage.

GRASS MINIMUM TEMPERATURE - the minimum temperature indicated by a thermometer freely exposed in an open situation at night with its bulb at the same level as the tips of shorn grass.

ICE NUCLEATION TEMPERATURE - the temperature at which ice-forming nuclei (very small particles) cause water to freeze.

INTRACELLULAR - within the cell.

KATABATIC FLOW - downslope air movement caused by the increased density of cold air.

LATENT HEAT - the heat released per unit mass as water vapour in the air changes phase to liquid or ice.

LONGWAVE RADIATION - radiation of energy in the range of wavelengths 3 - 100 μm.

NET RADIATION - at night, the difference between the longwave radiation emitted upward from the ground surface and downward from the sky.

PLASMOLYSIS -separation of the cell membrane from the cell wall.

PROFILE - a graph of an atmospheric quantity showing changes with height or distance.

RADIATION - the process by which electromagnetic energy is propagated through space.

RADIATION FROST - frost caused by a lowering of surface temperature as result of radiative heat loss to the atmosphere.

SENSIBLE HEAT - thermal energy that can be sensed with a thermometer.

SKY VIEW FACTOR - the ratio of the amount of the sky seen from a given point on a surface to that potentially available if unobstructed.

SOLAR RADIATION - (short wave) radiation of energy in the range of wavelengths 0.15 - 3 μm.

SUBLIMATION - the transition of a substance directly from the solid to the vapour phase or from the vapour to the solid phase.

SUPERCOOLING - cooling of water below 0°C without ice formation.

6 REFERENCES

Andre, J.C. and L. Mahrt. 1982. The nocturnal inversion and influence of clear air on radiative cooling. J. Atmos. Sci. 39:864-878.

Bjor, K. and M. Sandvik. 1984. Summer frost problems in a locality in Trondelag. *In*: Ecology and management of forest biomass production systems. R. Pertu (editor) Dep. Ecol. Environ. Res., Swed. Univ., Agric. Sci. Rep. 15:19-28.

Black, T.A., R.L. Fleming, R. Adams, and N. Eldridge. 1988. Site preparation to minimize seedling water and temperature stress in backlog areas in the Southern Interior. 1986-87 Annual Report to the Southern Interior FRDA Technical Advisory Committee. B.C. Min. of For., Victoria, B.C.

Black, T.A., R.L. Fleming, R.J. Stathers, and K.K. Chan. 1987. Site preparation and planting procedures to minimize seedling water and temperature stress in backlog areas in the Southern Interior. 1986-87 Annual Report to the Southern Interior FRDA Technical Advisory Committee. B.C. Min. of For., Victoria, B.C.

Bootsma, A. 1976. Estimating minimum temperature and climatological freeze risk in hilly terrain. Agric. Meteorol. 16:425-443.

Cannell, M.G.R. 1984. Spring frost damage on young *Picea sitchensis*. I. Occurrence of damaging frosts in Scotland compared with Western North America. Forestry 57:159-175.

Christersson, L. 1971. Frost damage resulting from ice crystal formation in seedlings of Spruce and Pine. Physiol. Plant. 25:273-278.

_____. 1983. Frost damage during the growing season. *In*: Plant production in the North. Proc. Plant Adaptation Workshop. Sept. 1983. A. Kaurin, O. Juntilla, and J. Nilsen (editors). Norwegian Univ. Press, Tromso, Norway.

Christersson, L. and R. Sandstedt. 1978. Short-term variation in needles of *Pinus sylvestris* L. Can. J. For. Res. 8:480-482.

Coates, D. 1988. Effects of shrub and herb competition on conifer regeneration and microclimate in the rhododendron-vaccinium-menziesia community of south-central B.C. M.Sc. thesis. Oreg. State Univ., Corvallis, Oreg., U.S.A.

Cochran, P.H. 1969. Lodgepole pine clearcut size affects minimum temperature near the ground surface. U.S.Dept. Agric., For. Serv., Res. Pap. PNW-86.

Cochran, P.H. and C.M. Bernstein. 1979. Tolerance of lodgepole and ponderosa pine seedlings to low night temperatures. For. Sci. 19:272-280.

Cremer, K.W. and R. Leuning. 1985. Effects of moisture on soil temperature during radiation frost. Aust. For. Res. 15:33-42.

DeLucia, E.H. 1987. The effect of freezing nights on photosynthesis, stomatal conductance, and internal CO_2 concentration in seedlings of Engelmann spruce (*Picea engelmannii* Parry). Plant, Cell and Environ. 10:333-338.

DeLucia, E.H. and W.K. Smith. 1987. Air and soil temperature limitations on photosynthesis in Engelmann spruce during summer. Can. J. For. Res. 17:527-533.

Emmingham, W.H. 1985. Prescribing shelterwoods in the Cascade and Siskiyou mountains of Oregon: considering topography, density and species. *In*: Proc. Workshop on Shelterwood Management Systems. J.W. Mann and S.D. Tesch (editors). Oreg. State Univ., For. Res. Lab., Corvallis, Oreg.

Geiger, R. 1950. The climate near the ground. 2nd ed. Harvard Univ. Press, Cambridge, Mass. 482 p.

Glerum, C. 1985. Frost hardiness of coniferous seedlings: principles and applications. *In*: Proc. Evaluating Seedling Quality: Principles, Procedures, and Predictive Abilities of Major Tests. M.L. Duryea (editor) ISBN 0-8743

Gusta, L.V. 1983. Freezing resistance in plants. *In*: Plant production in the North. Proc. Plant Adaptation Workshop. Sept. 1983. A. Kaurin, O. Juntilla, and J. Nilsen (editors). Norwegian Univ. Press, Tromso, Norway.

Hall, M. 1985. Establishment of radiata pine on a high altitutude, second rotation site. II. Effects of site preparation on early survival and growth. Aust. For. 48(2): 79-83.

Hocevar, A. and J. D. Martsolf. 1971. Temperature distribution under radiation frost conditions in a central Pennsylvania valley. Agric. Meteorol. 8: 371-383.

Hungerford, R.D. and R.E. Babbitt. 1987. Overstory removal and residue treatments affect soil surface, air, and soil temperature: implications for seedling survival. U.S. Dept. Agric., For. Serv., Intermountain Res. Stn. Res. Paper INT-377.

Kalma, J.D., G.P. Laughlin, A.A. Green, and M.T. O'Brien. 1986. Minimum temperature surveys based on near surface air temperature measurements and airborne thermal scanner data. J. Climatol. 6:413-430.

Kramer, P.J. and T.T. Kozlowski. 1979. Physiology of woody plants. Academic Press, New York, N.Y. 811 p.

Lake, J.V. 1956. The temperature profile above bare soil on clear nights. Q.J.R. Meteorol. Soc. 82:187-197.

Lake, J.V. 1956. The temperature profile above bare soil on clear nights. Q.J.R. Meteorol. Soc. 82:187-197.

Larcher, W. 1981. Effects of low temperature stress and frost injury on plant productivity. *In*: Physiological processes limiting plant productivity. C.B. Johnson (editor). Butterworths, London. 395 p.

Larcher, W. 1985. Kalte und frost. *In*: Sorauer, P. Handbuch der Pflanzenkrankheiten, Vol 1. 7th ed. Parey, Berlin, pp.107-326.

Laughlin, G.P. 1982. Minimum temperature and lapse rate in complex terrain: influencing factors and prediction. Arch. Met. Geoph. Biokl. Ser. B. 30:141-152.

Laughlin, G.P. and J.D. Kalma. 1987. Frost hazard assessment from local weather and terrain data. Agr. For. Meteorol. 40:1-16.

Leikola, M. and R.Rikala. 1983. The influence of nurse crops on stand temperature conditions and the development of Norway spruce seedlings. Folia For. 559:1-33.

Leuning, R. 1988. Leaf temperatures during radiation frost. Part II. A steady state theory. Agric. For. Meteorol. 42:135-155.

Leuning, R. and K.W. Cremer. 1988. Leaf temperatures during radiation frost. Part II. Observations. Agric. For. Meteorol. 42:121-133.

Levitt. J. 1980. Responses of plants to environmental stresses. Vol. 1. Chilling, freezing and high temperature stresses. Academic Press, New York, N.Y.

Ludlow, M.M. and M.J. Fischer. 1976. Influence of surface litter on frost damage. Aust. Inst. Agric. Sci. J. 42:134-136.

Lundmark, T. and J.E. Hallgren. 1987. Effects of frost on shaded and exposed spruce and pine seedlings planted in the field. Can. J. For. Res. 17:1197-1201.

Mannins, P.C. and B.L. Sawford. 1979. Katabatic winds: a field case study. Q.J.R. Meteorol. Soc. 105:1011-1025.

Monteith, J.L. 1973. Dew. Q.J.R. Meteorol. Soc. 83:322-344.

Nunez, M. and D.M. Bowman. 1986. Nocturnal cooling in a high altitude stand of Eucalyptus delagatensis as related to stand density. Aust. For. Res. 16:185-197.

Nunez, M. and D.Sander. 1982. Protection from cold stress in a Eucalyptus shelterwood. J. Climatol. 2:141-146.

Odin, H., B. Magnusson, and P.O. Backstrom. 1984. Effect of low shelterwood on minimum temperature near the ground. *In*: Ecology and management of forest biomass production systems. R. Pertu (editor). Swed. Univ., Agric. Sci. Rep. 15:77-99.

Oke, T.R. 1970. The temperature profile near the ground surface on calm clear nights. Q.J.R. Meteorol. Soc. 96:14-23.

Pegg, R.E. and P.A. Armstrong. 1974. Delineation and reforestation of frost sites in the Yarraman area. Res. Paper #6. Dep. of For., Brisbane, Australia.

Raitio, H. 1987. Site elevation differences in frost damage to Scots pine (*Pinus sylvestris*). For. Ecol. Manage. 20:299-306.

Rosenberg, N.J., B.L. Blad, and S.B. Verma. 1983. Microclimate, the biological environment. 2nd ed. John Wiley and Sons, New York, N.Y.

Sakai, A. and W. Larcher. 1987. Frost survival of plants, responses and adaptation to freezing stress. Springer-Verlag, Berlin.

Vyse, A. 1988. Improving summer planting in the southern interior of B.C. FRDA Project 3.42, B.C. Min. For., Research Memo No. 28.

Weiser, C.J. 1970. Cold resistance and injury in woody plants. Science 169:1269-1278.